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Analysis of triggering mechanism of deep-seated landslide induced by heavy rainfall

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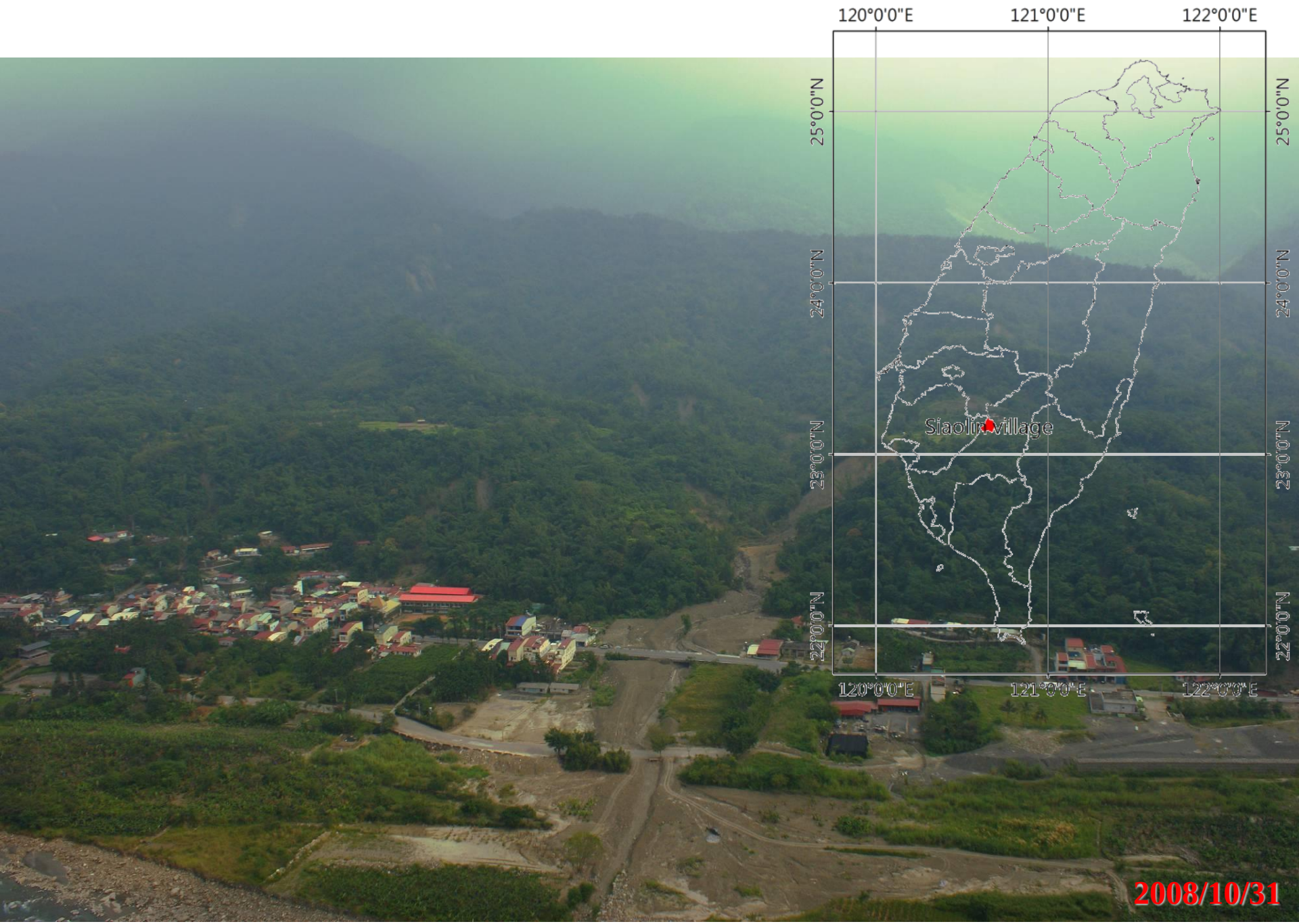
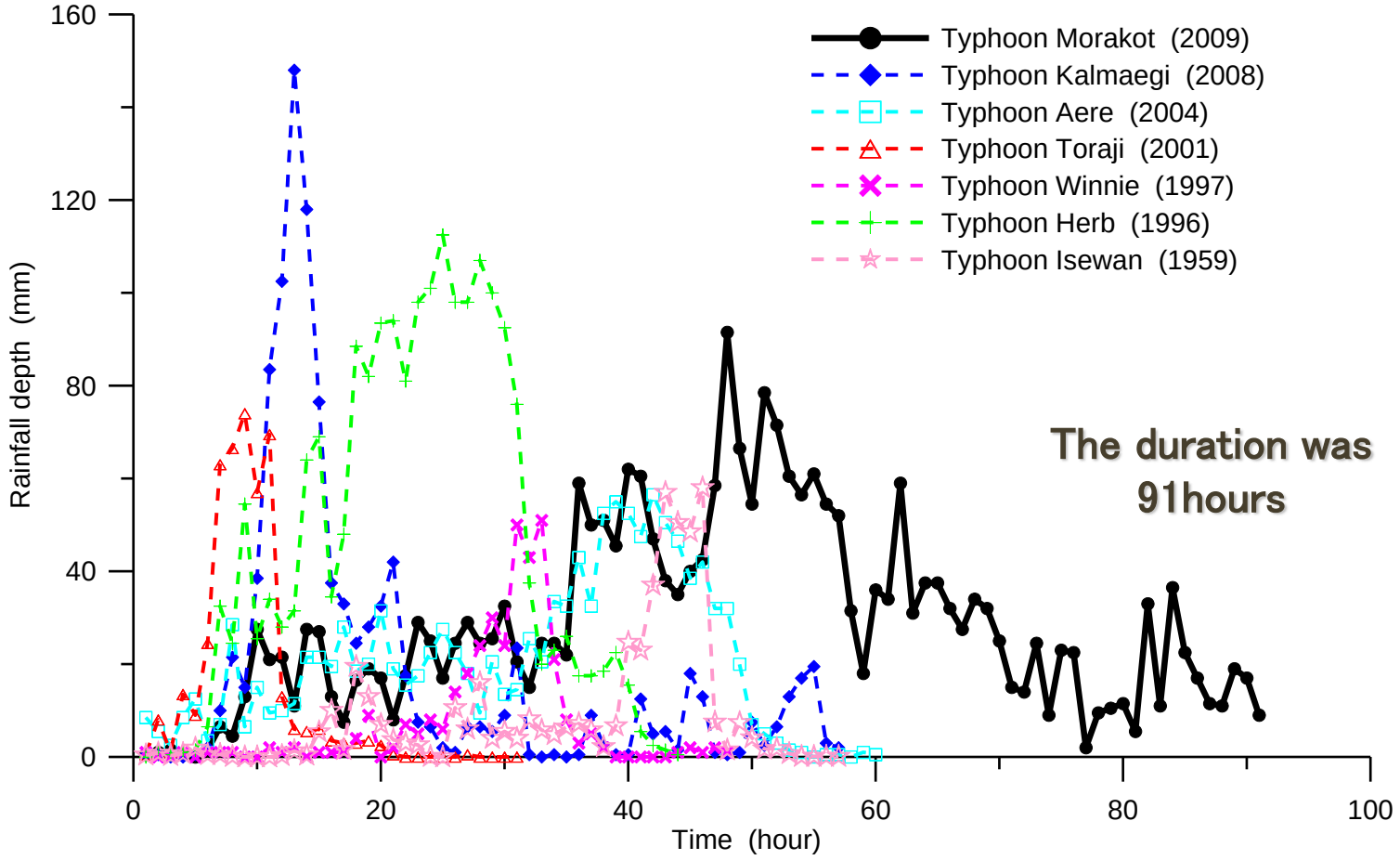
Background

- Large amount of rainfall was recorded at middle to south part of Taiwan due to Typhoon Morakot from August 6 to 9, 2009
- More than 400 people were killed by a huge deep seated landslide at Shaolin village, Kaohsiung County
- The disaster was a compound disaster which includes landslides, debris flow and landslide dam formation and collapse

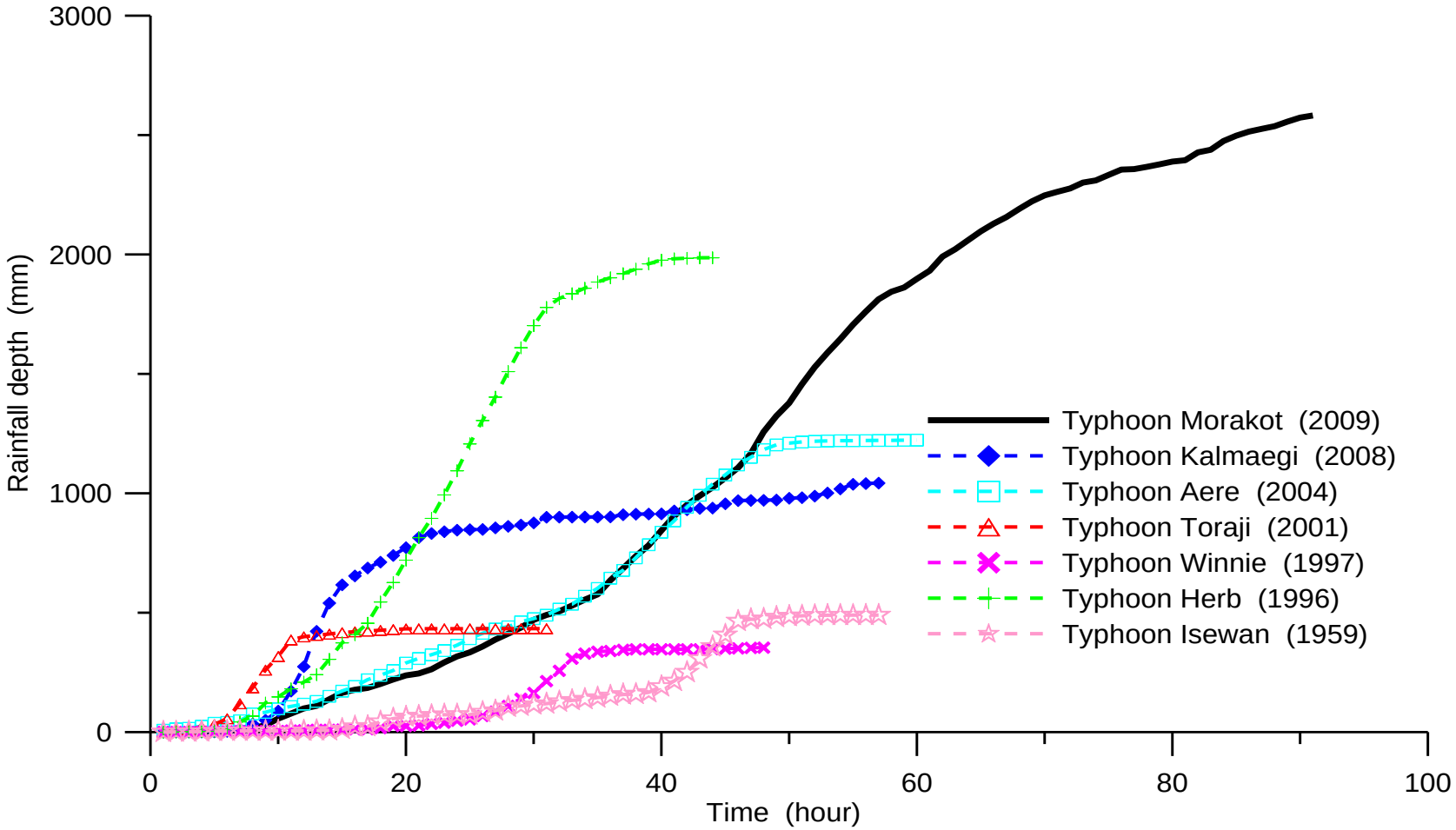

120°0'0"E
121°0'0"E
122°0'0"E
25°0'0"N
24°0'0"N
23°0'0"N
22°0'0"N
Siaolin village
2008/10/31


2003/6/5

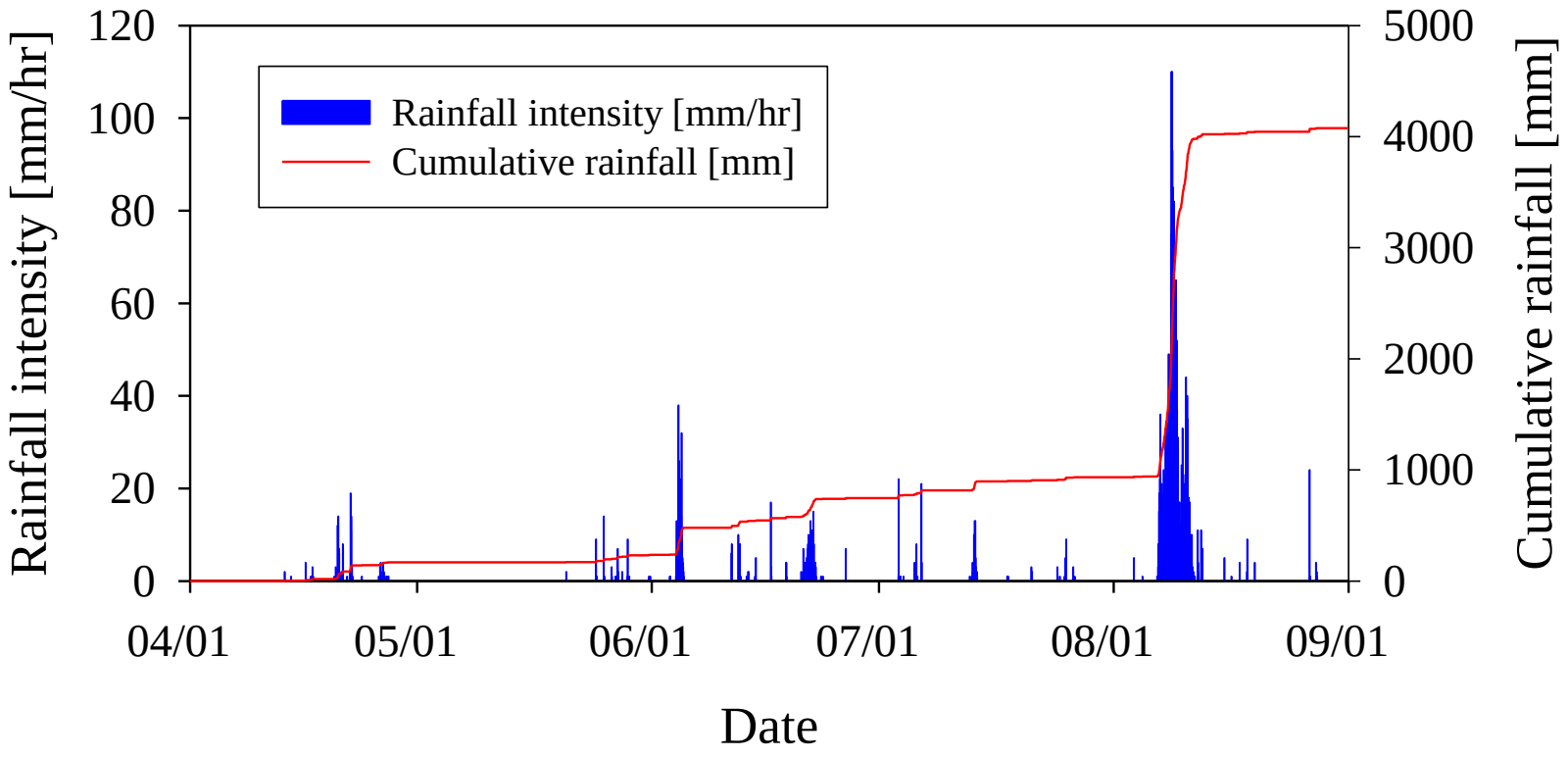
Comparison of intensity and duration of rainfall caused by past typhoons



Comparison of total precipitation by typhoons which hit Taiwan in the past



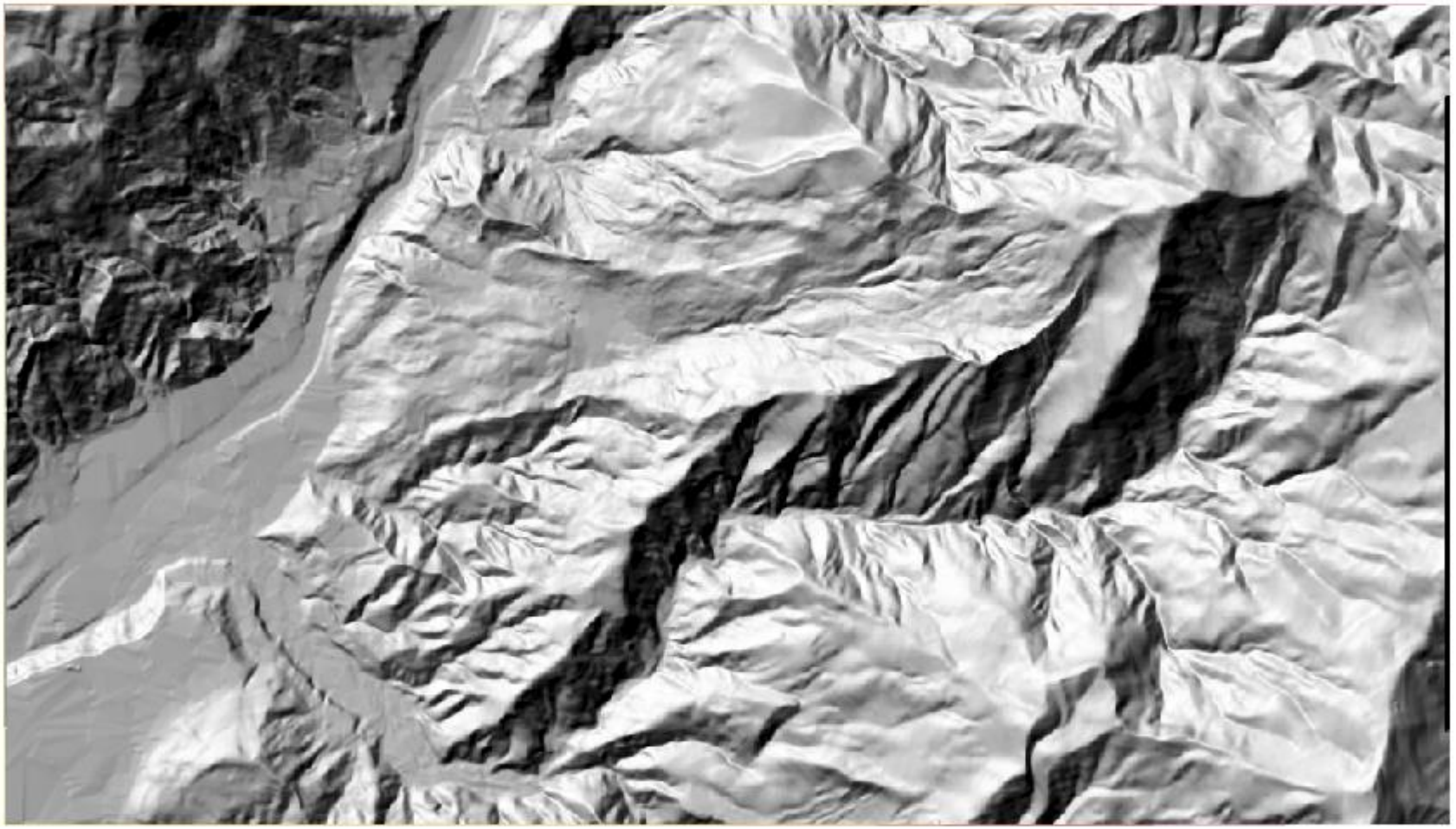
Rainfall at Shaolin village



Objectives

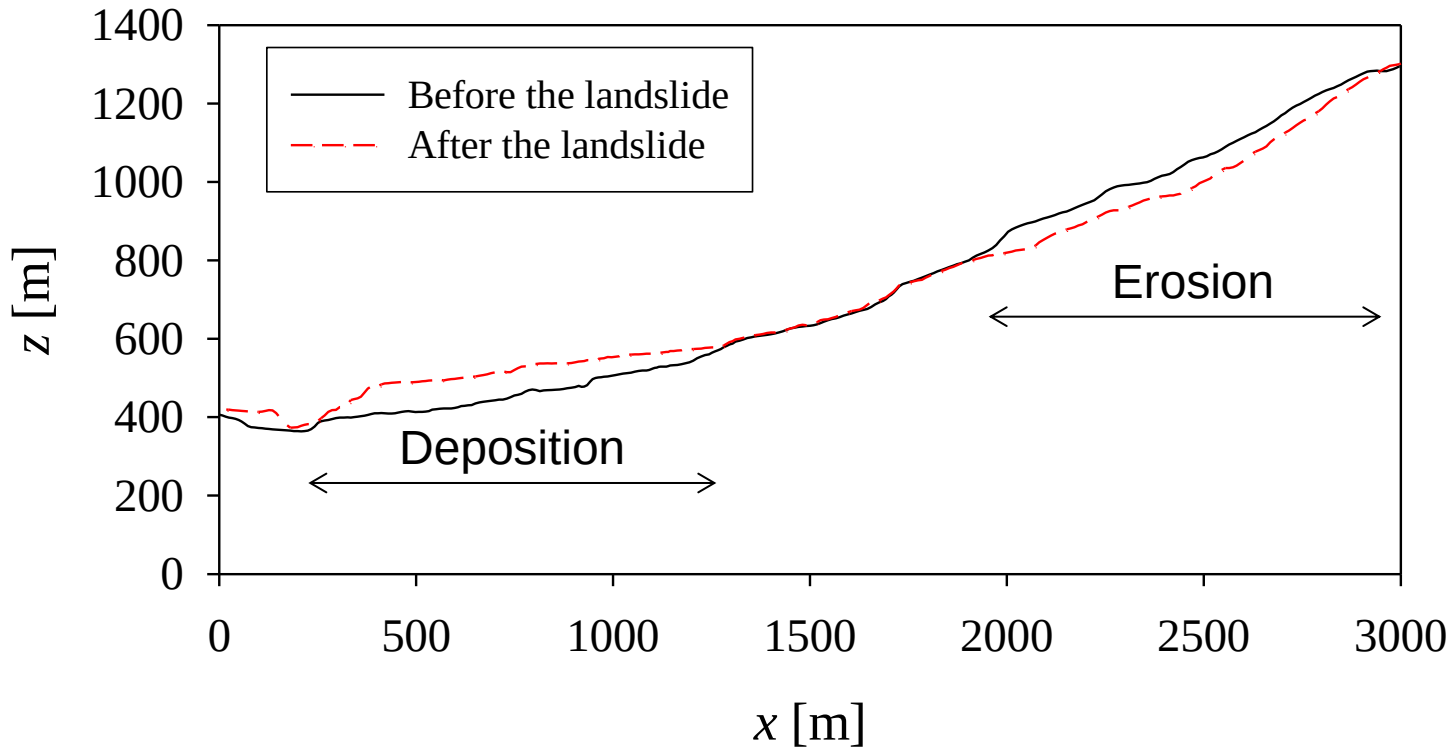
- Clarify the mechanism of the landslide occurrence
  - Analyze the size of landslide by GIS
  - Development of underground water table due to the rainfall event by numerical analysis
  - Multi phased landslide or single landslide?
- Discuss the critical rainfall for the landslide occurrence, regarding the rainfall due to Typhoon Morakot as an extreme rainfall event

Investigation of landslide size by GIS

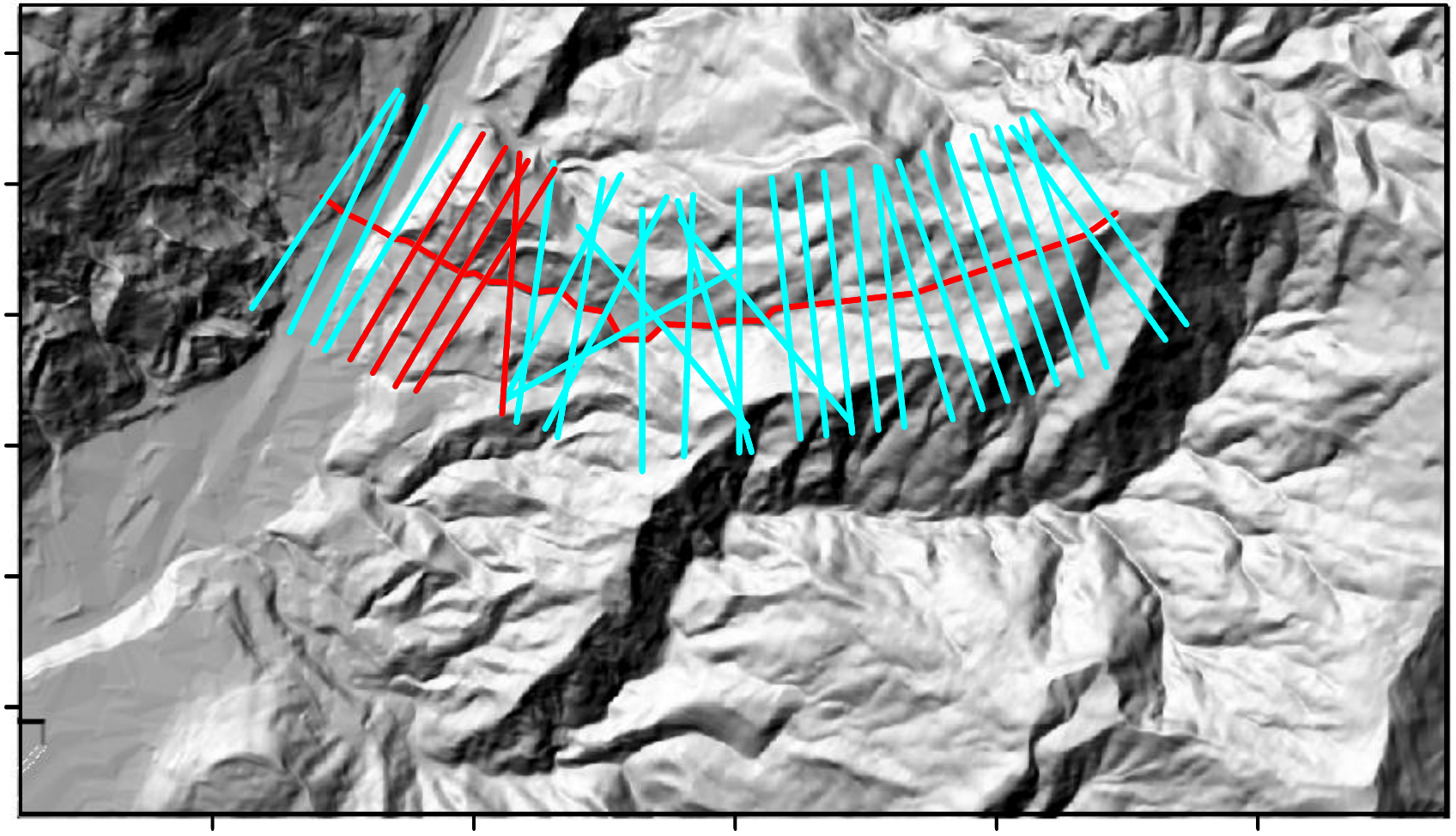


Longitudinal section

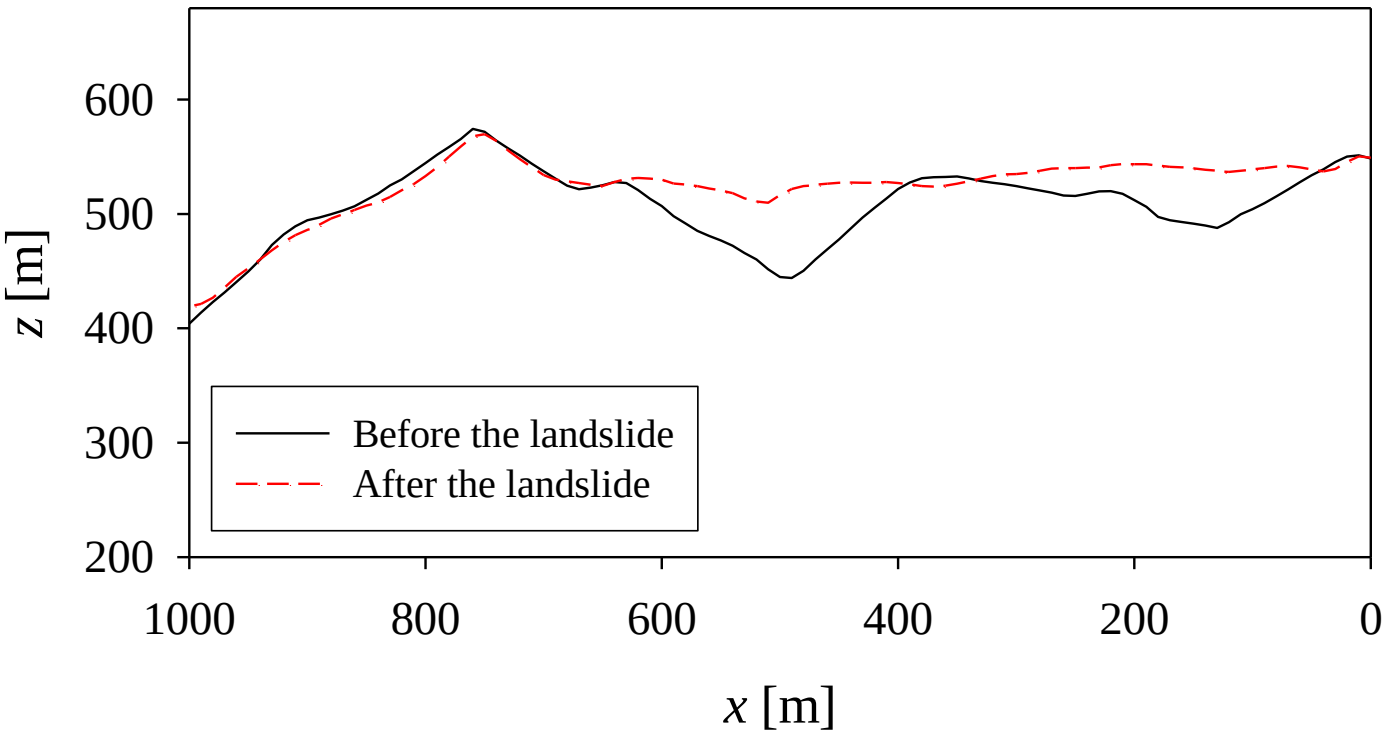
Longitudinal section

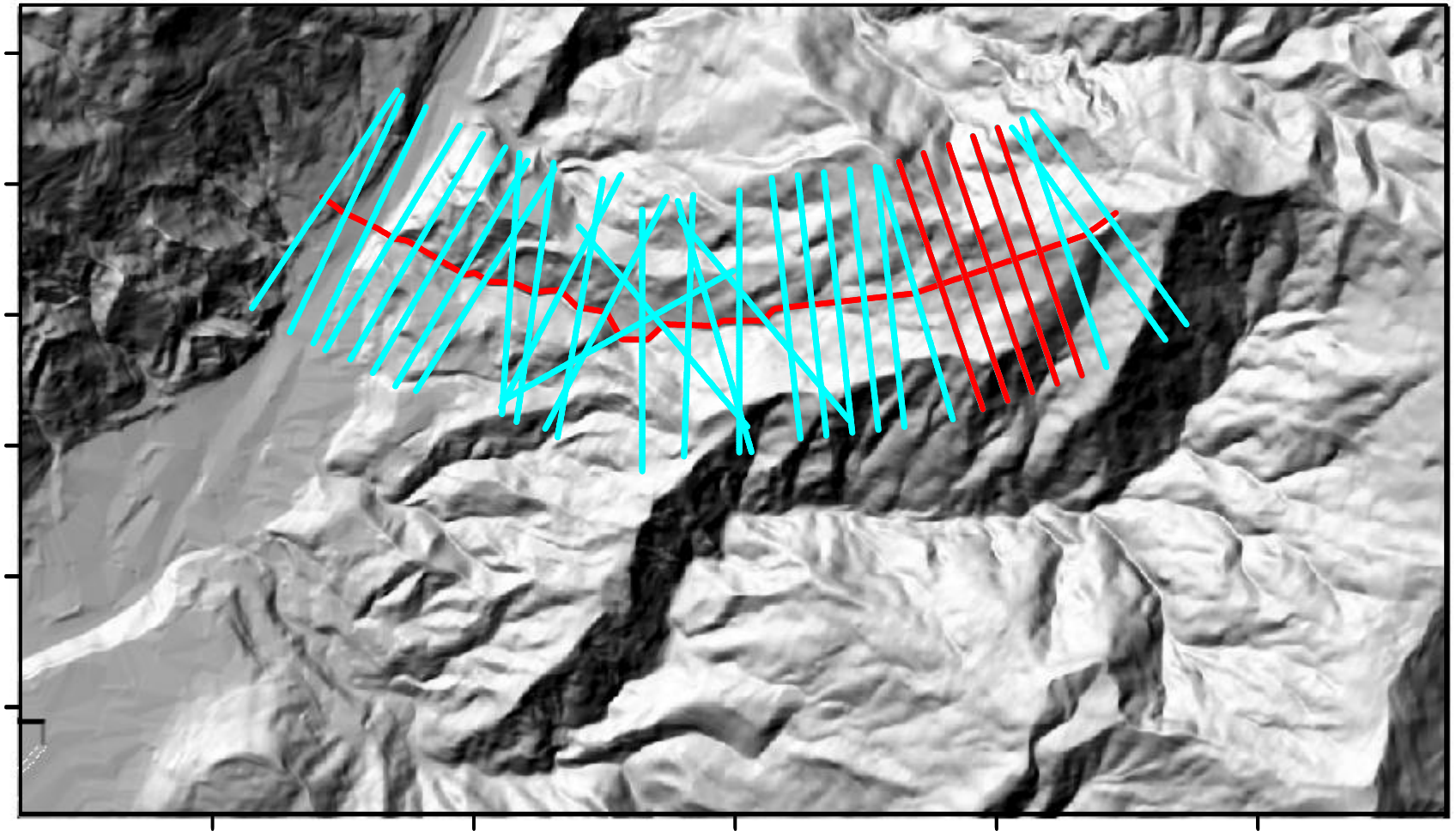


Cross section

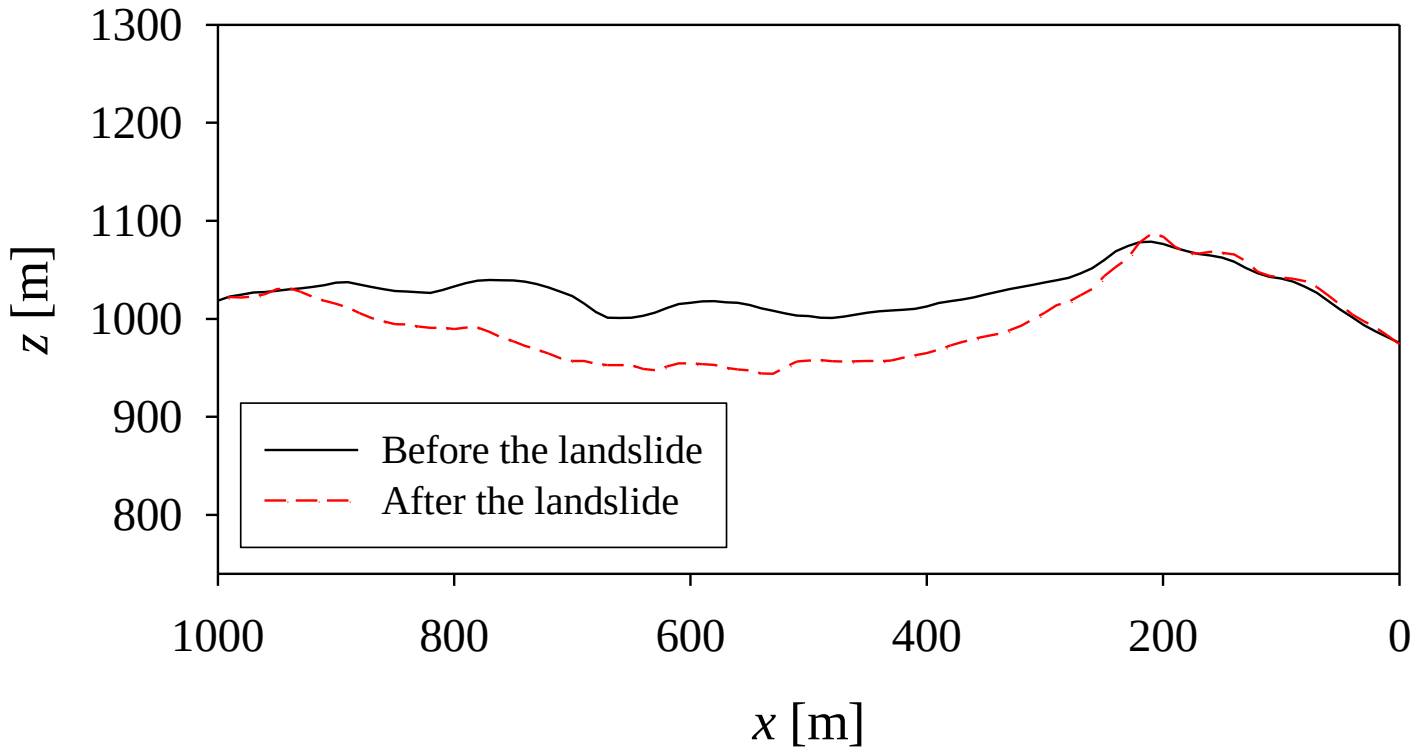


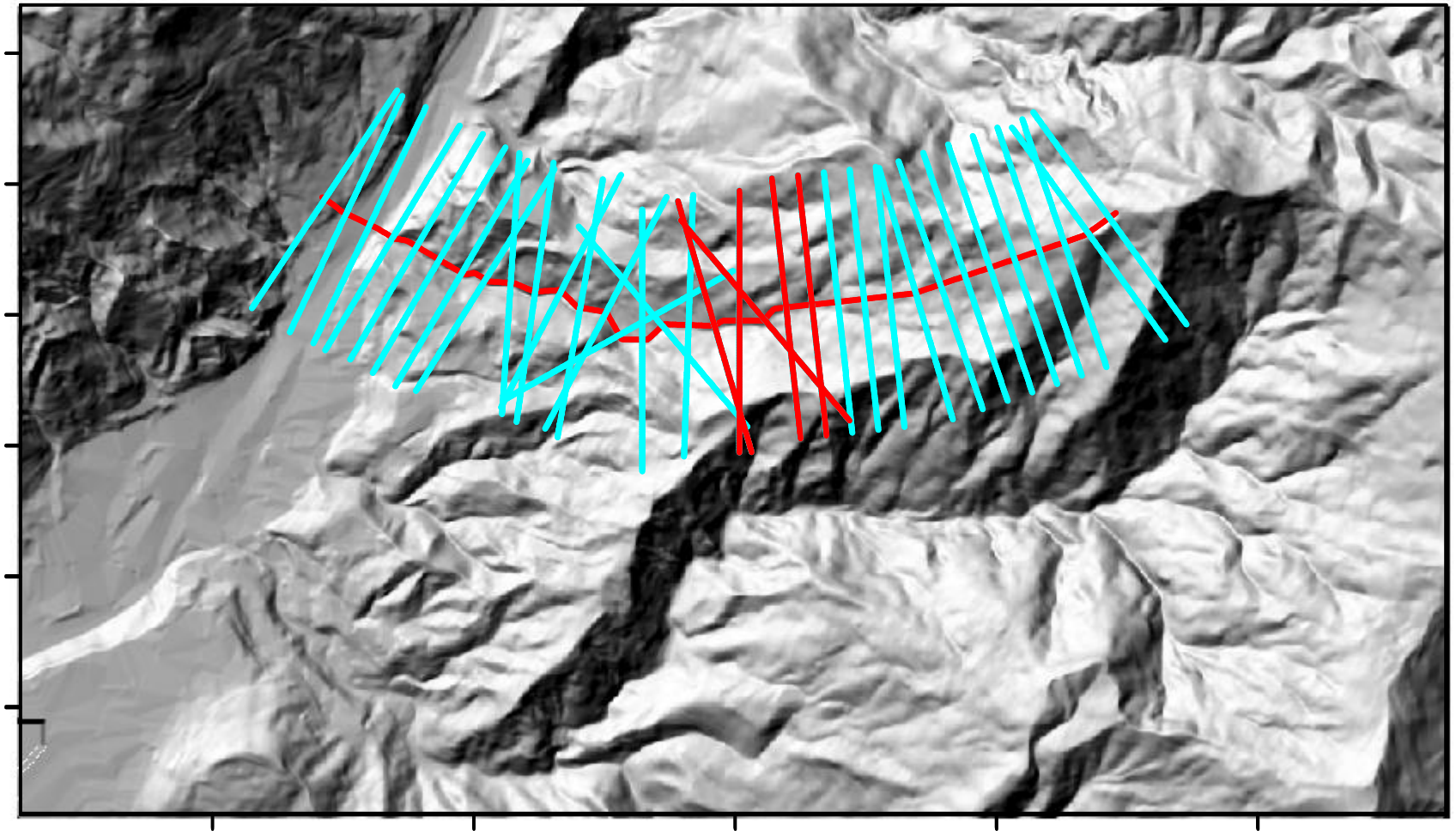
Cross section (deposition part)



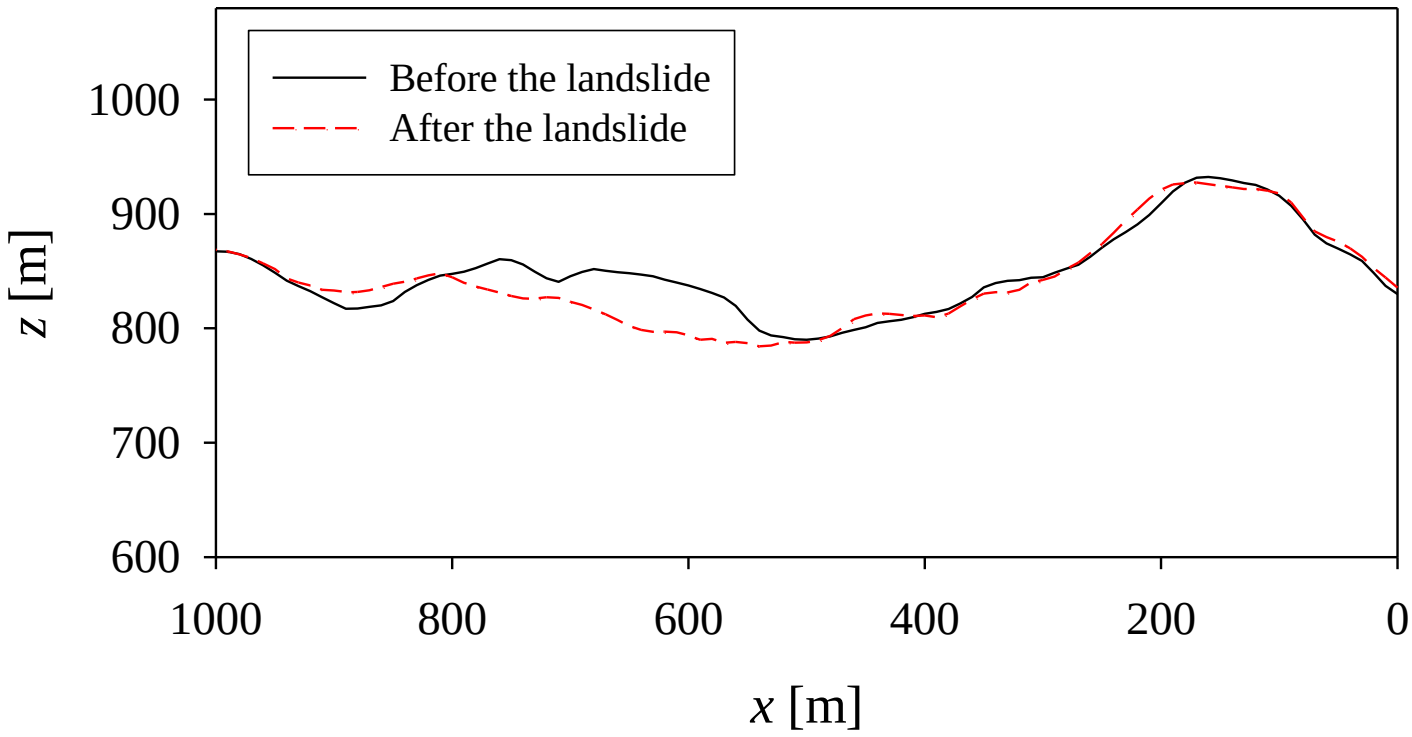


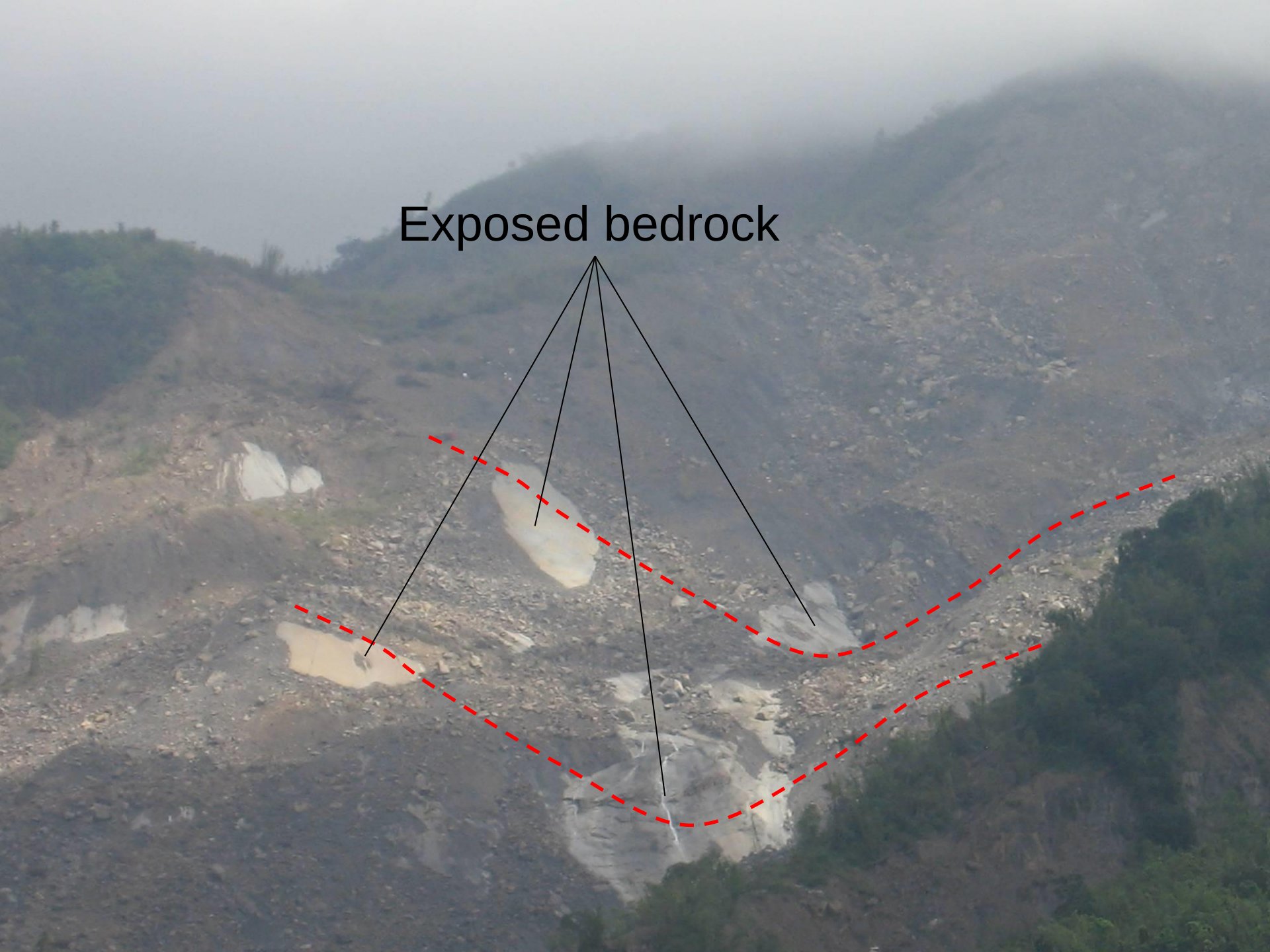
Cross section (erosion part)

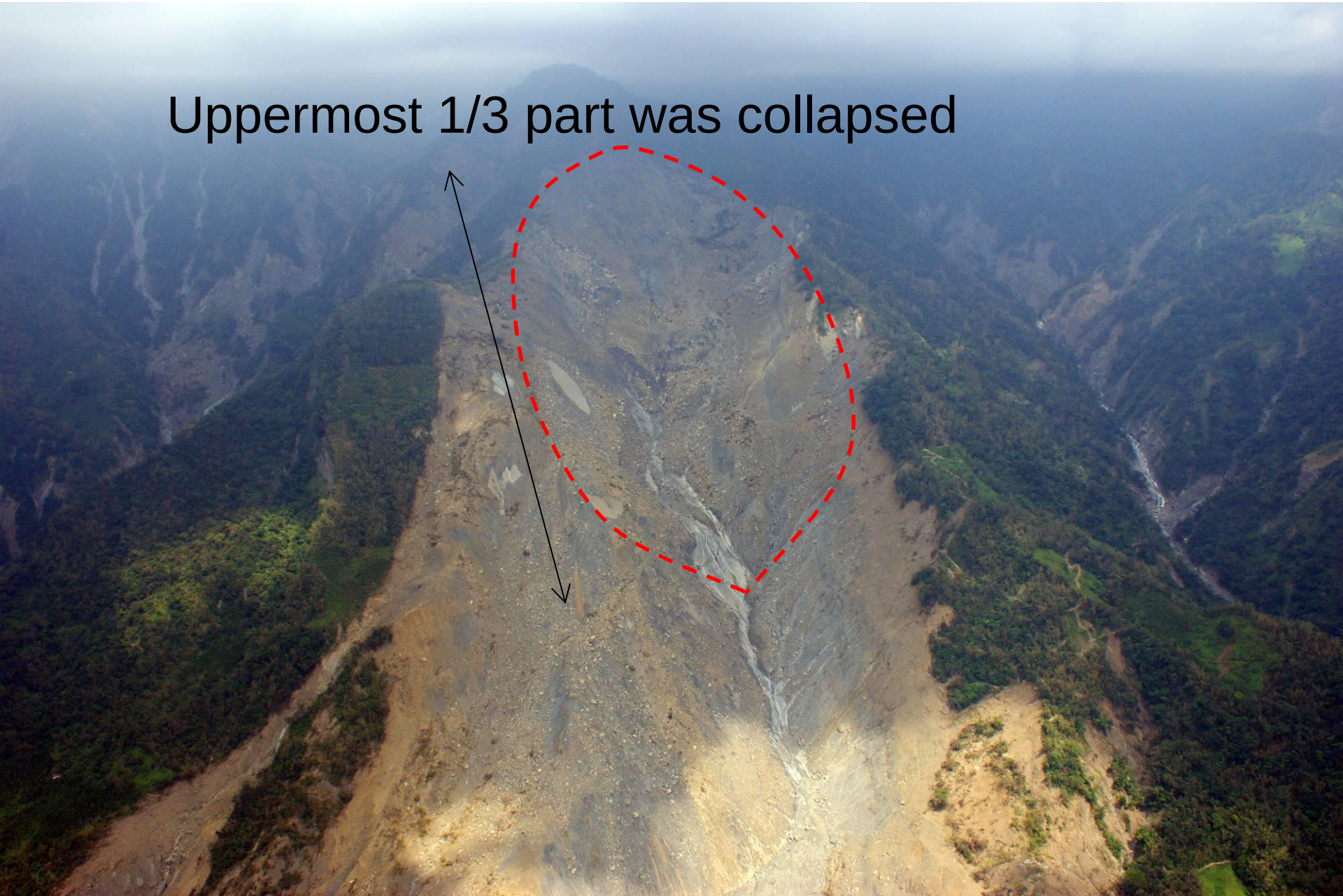




Cross section

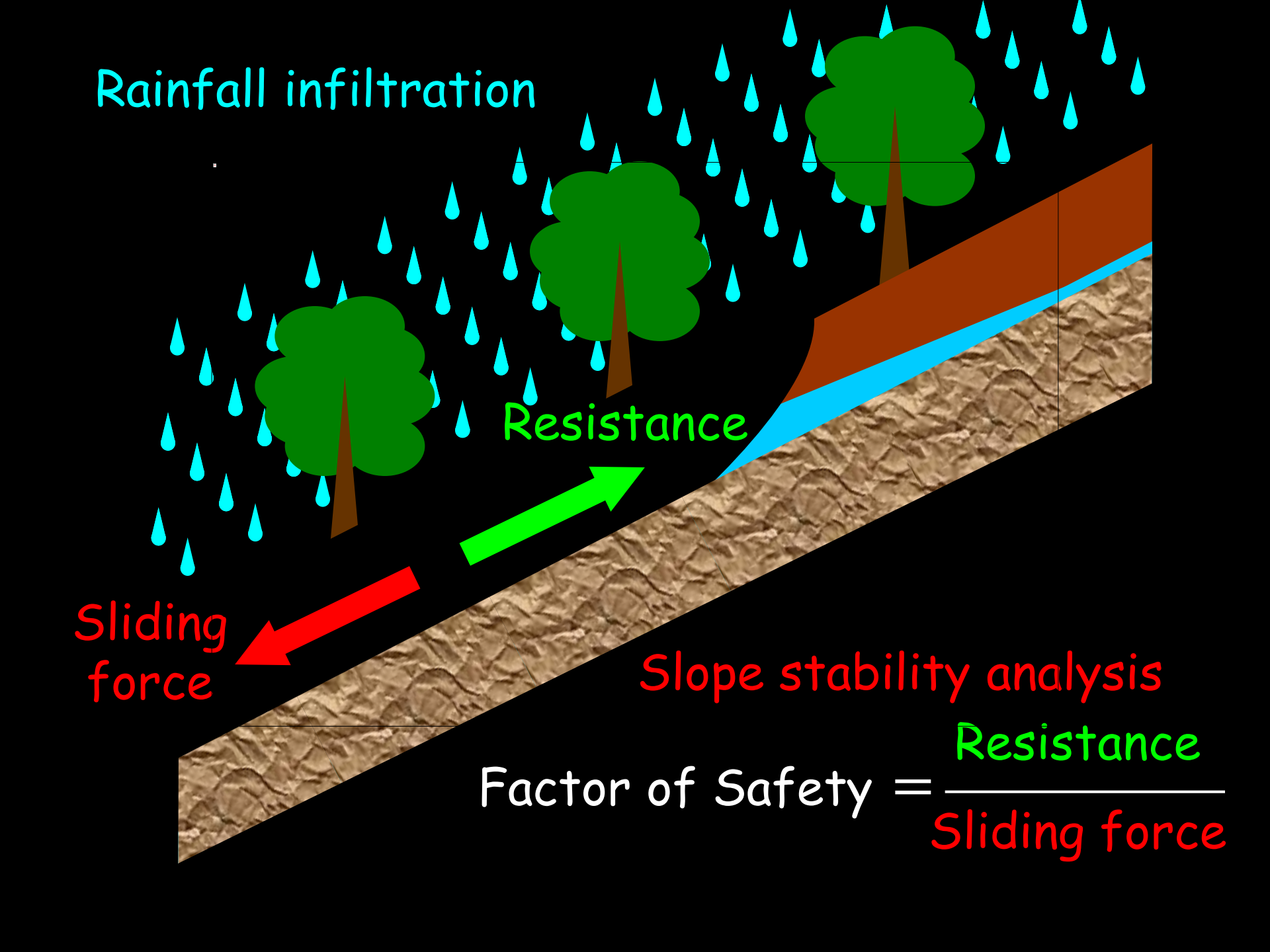



Exposed bedrock


Uppermost 1/3 part was collapsed

Numerical Analysis

- Rainwater infiltration
  - Richards Equation
  - Finite element method
- Slope stability
  - Simplified Jambu method
  - Dynamic programming method


Rainfall infiltration
Resistance
Sliding force
Slope stability analysis
Factor of Safety = Resistance / Sliding force

Rainwater infiltration analysis

Richards Equation

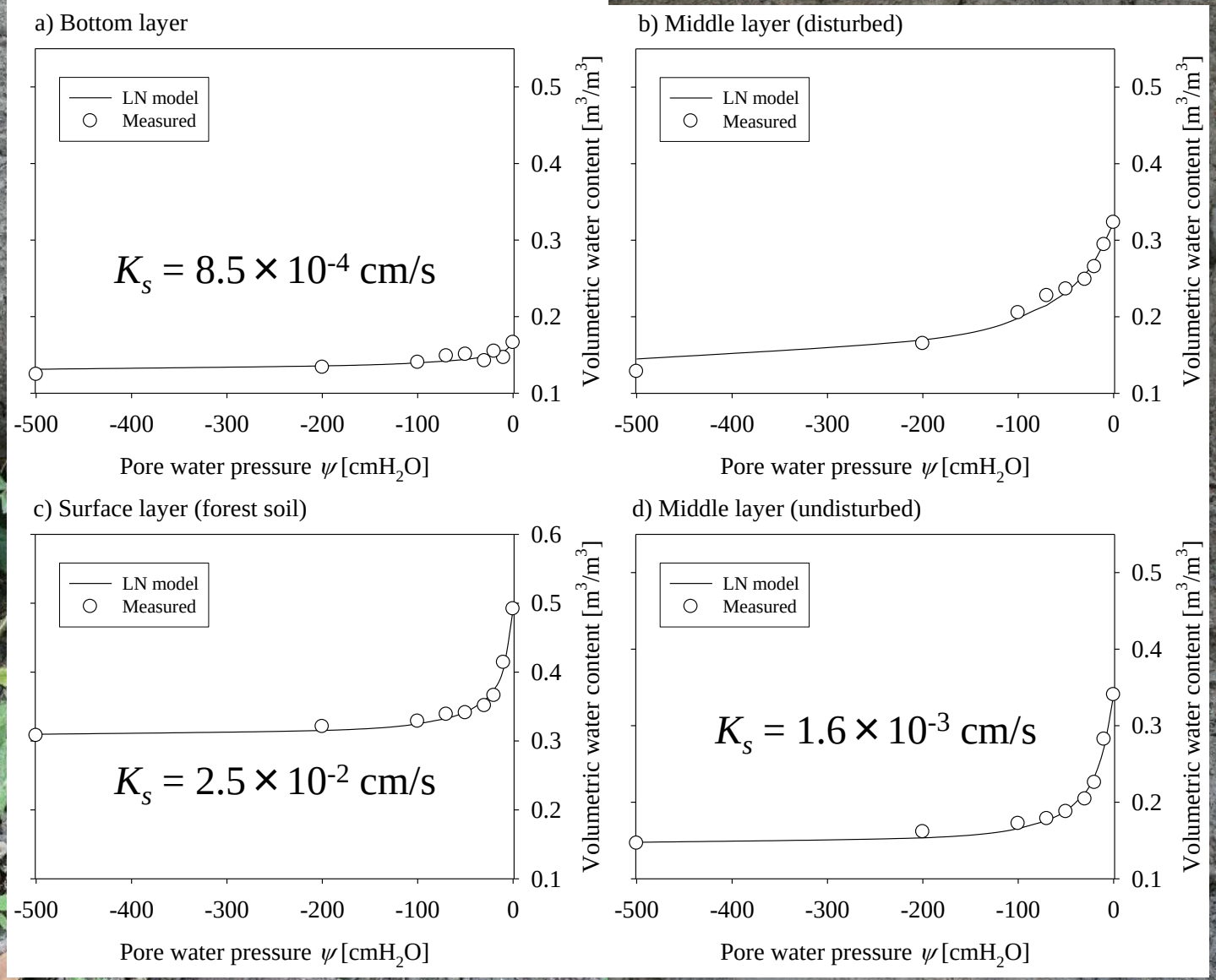
$$C\frac{\partial\psi}{\partial t}=\frac{\partial}{\partial x}\left(K_x\frac{\partial\psi}{\partial x}\right)+\frac{\partial}{\partial z}\left[K_z\left(\frac{\partial\psi}{\partial z}+1\right)\right]$$

Where: $C=\dfrac{\partial\theta}{\partial\psi}$

$$\theta=\theta_r+(\theta_s-\theta_r)Q\left\{\frac{\ln(\psi/\psi_m)}{\sigma}\right\}$$

$$K(\psi)=K_s\left[Q\left(\frac{\ln(\psi/\psi_m)}{\sigma}\right)\right]^{1/2}\left[Q\left(\frac{\ln(\psi/\psi_m)}{\sigma}+\sigma\right)\right]^2$$

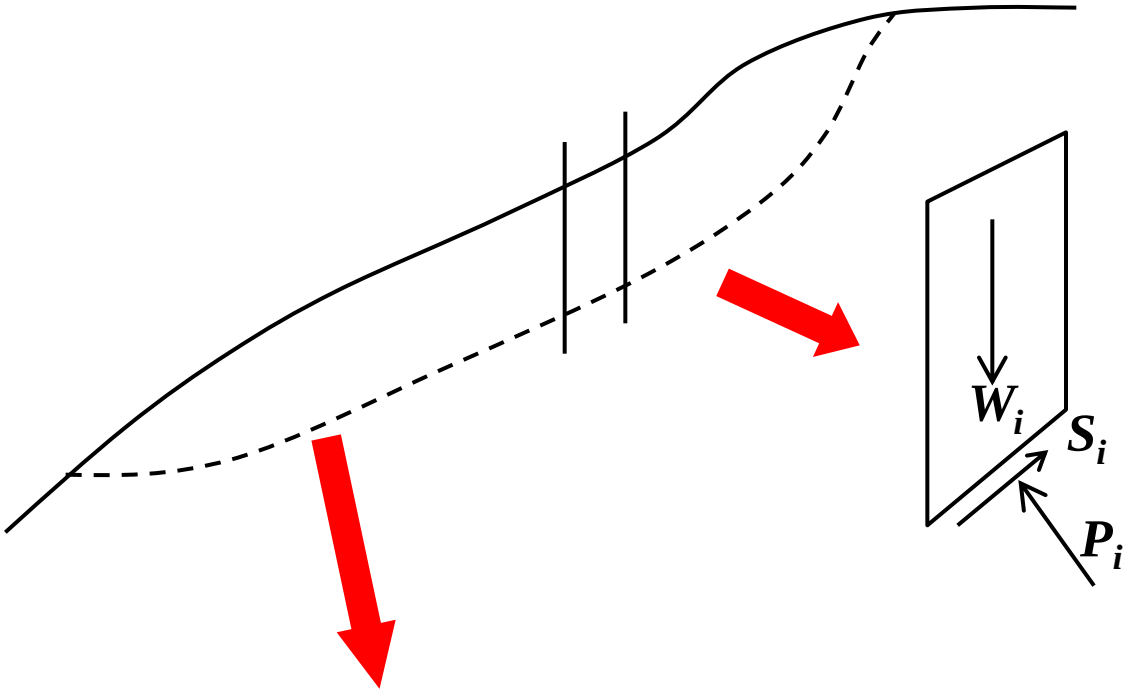
Soil Hydraulic Properties



Slope stability analysis

Janbu method:

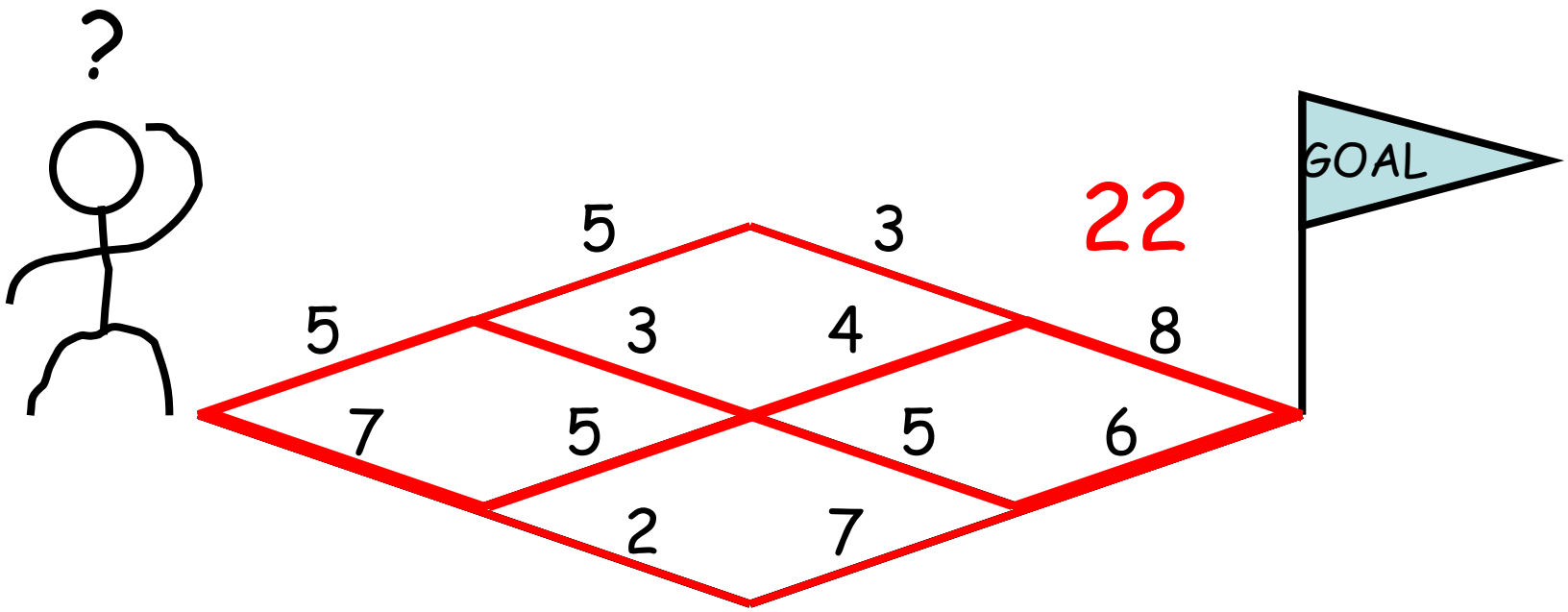
Applicable to any shape of slip surface



Dynamic Programming Method

Finding critical slip surface

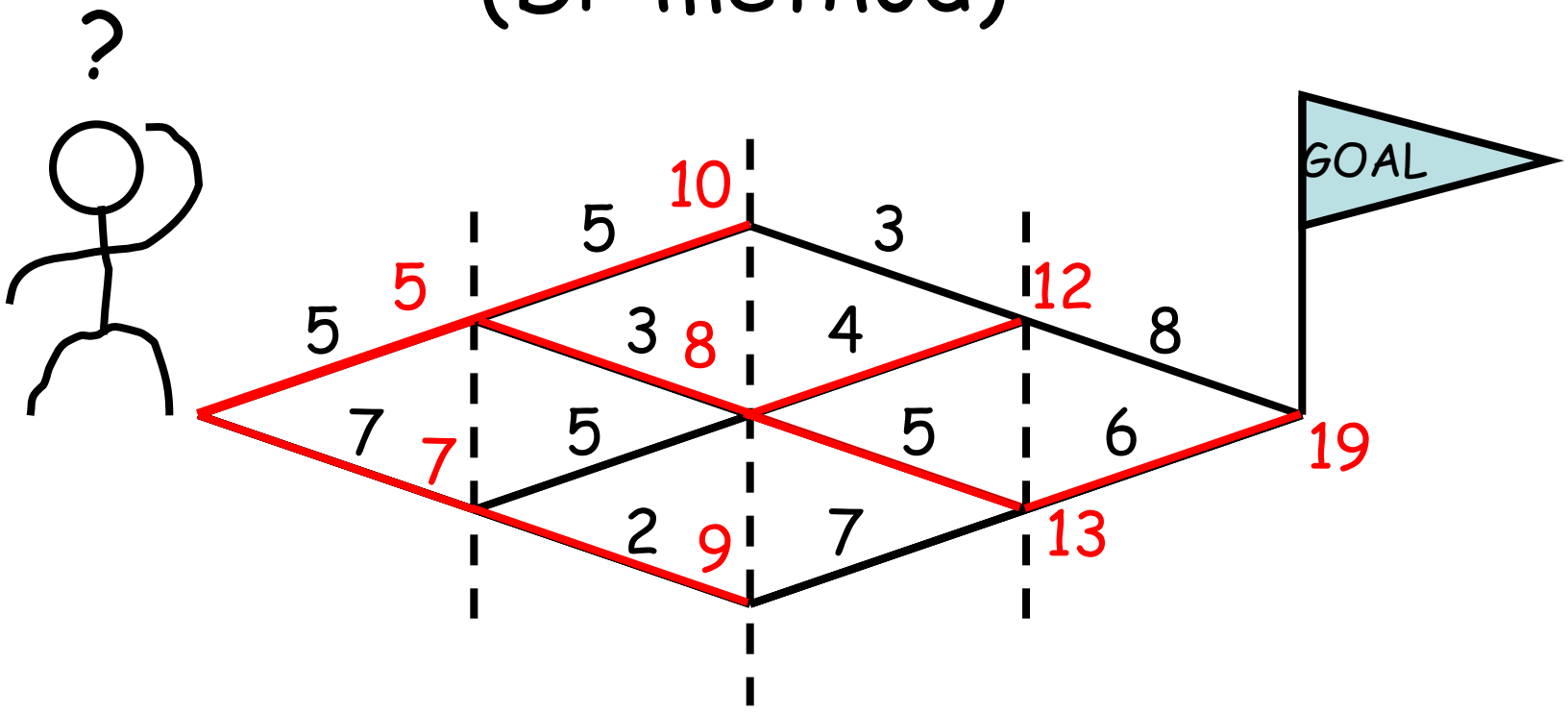
Assessing every pathway



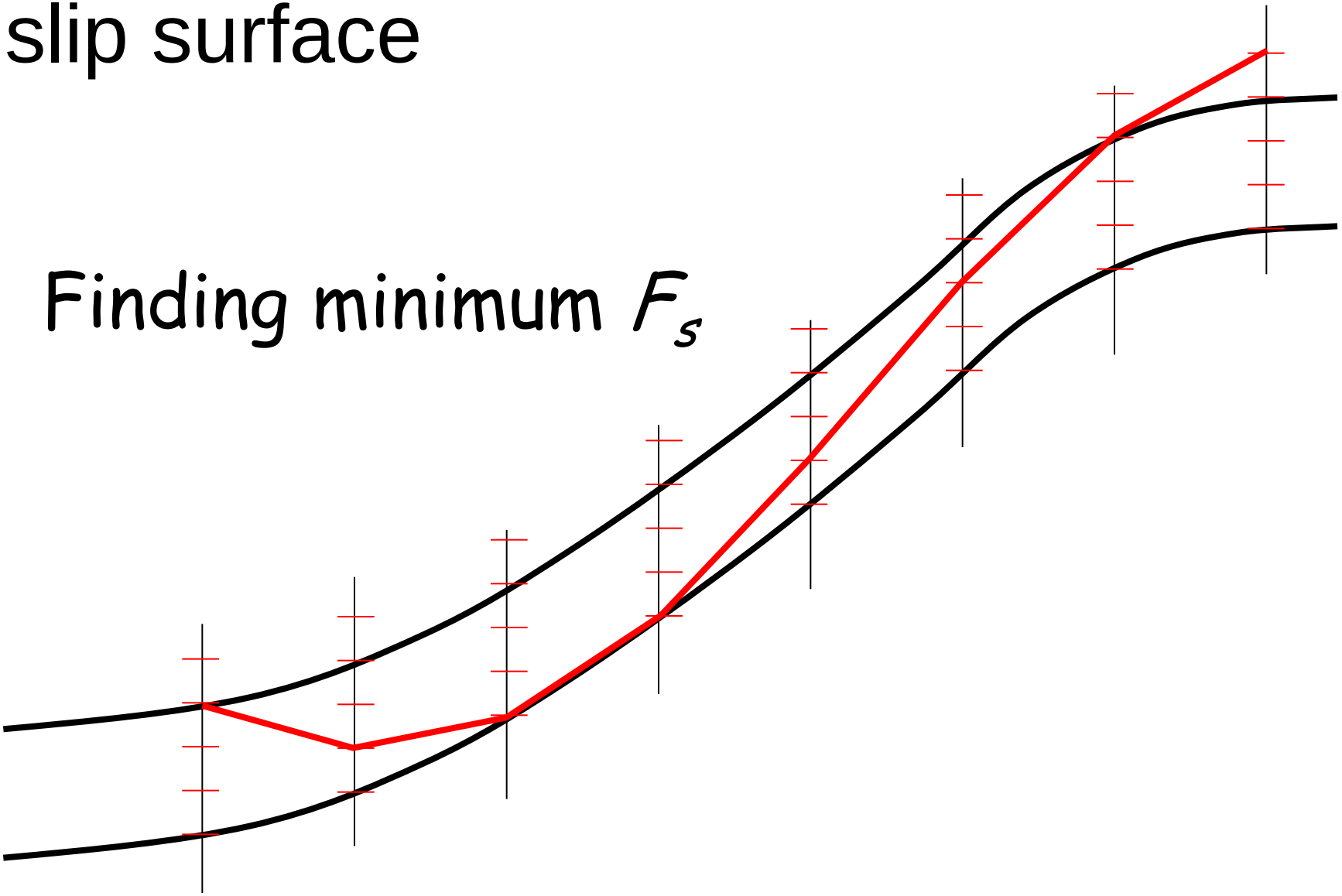
Finding critical slip surface

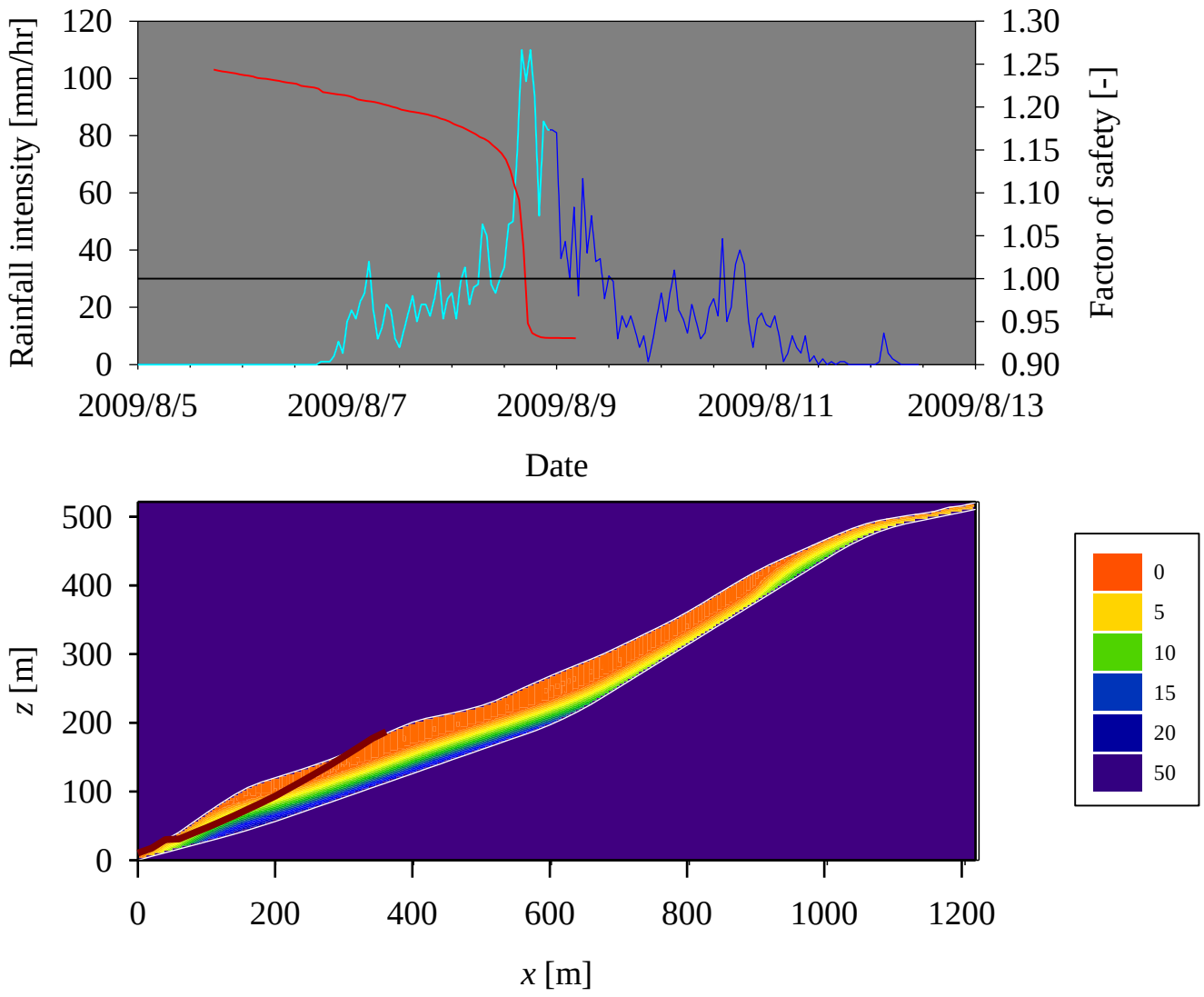
Dynamic programming method

(DP method)



Apply DP method to find the critical slip surface

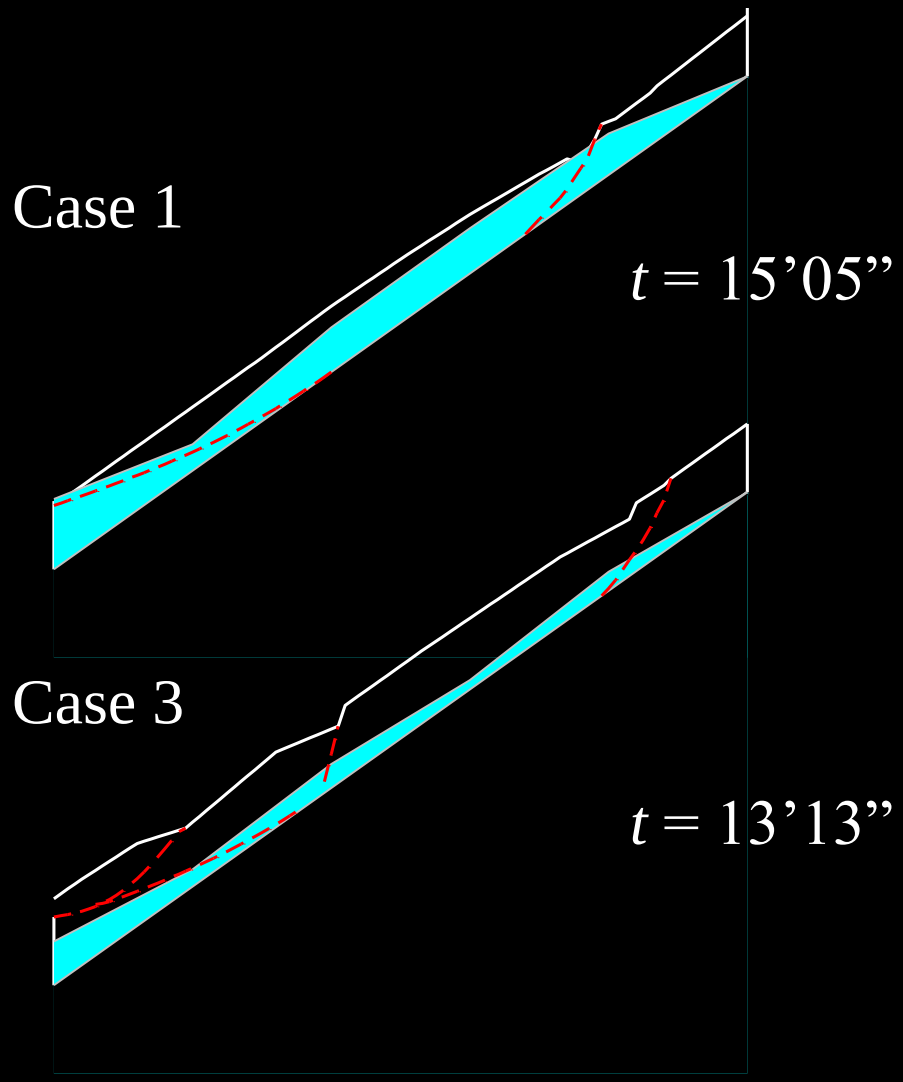



Rainfall intensity [mm/hr]
120
100
80
60
40
20
0
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
Factor of safety [-]
2009/8/5
2009/8/7
2009/8/9
2009/8/11
2009/8/13
Date
z [m]
500
400
300
200
100
0
0
200
400
600
800
1000
1200
x [m]
0
5
10
15
20
50

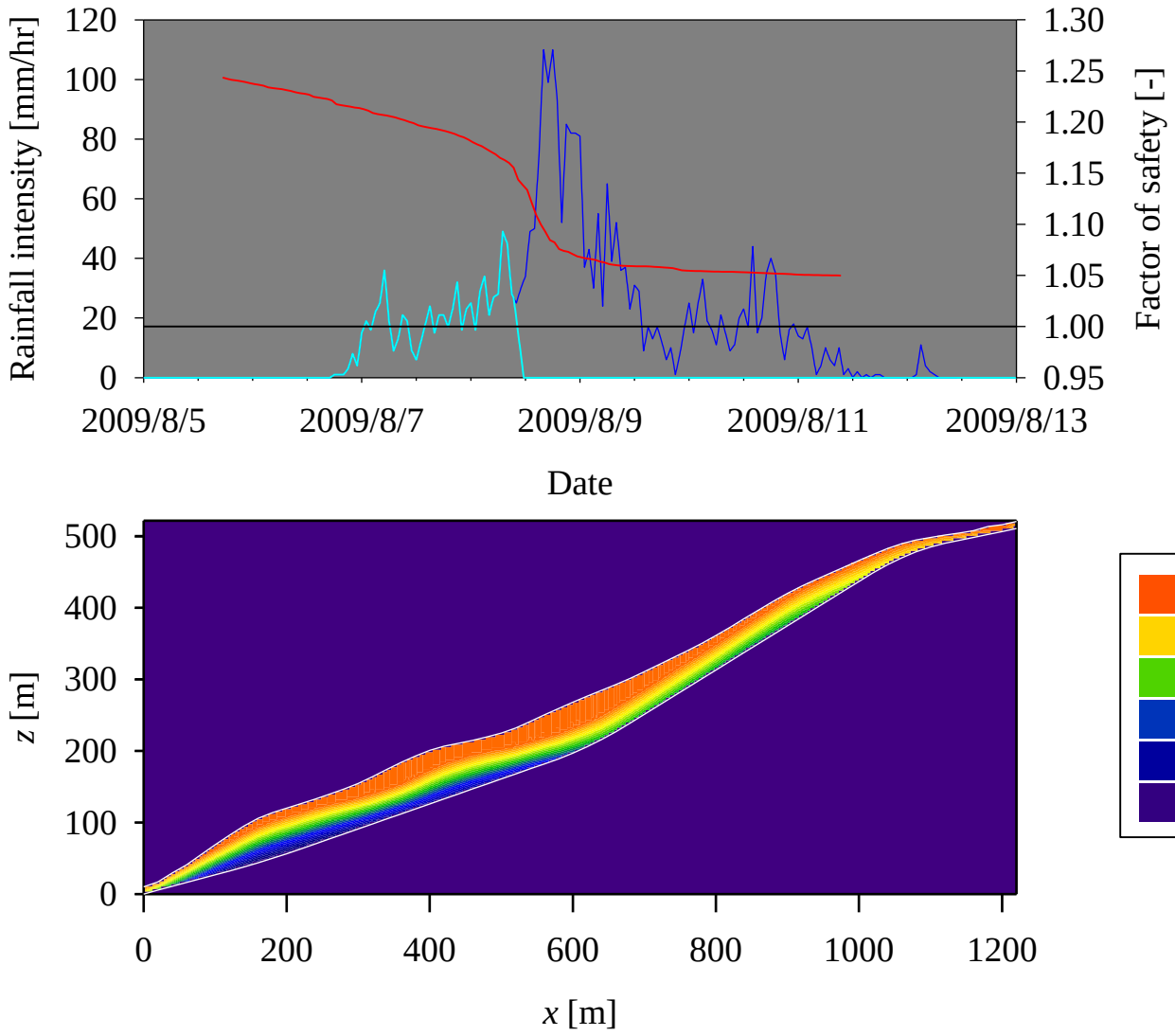
Flume experiment : Case 1 (Single collapse)

Flume experiment：Case 2 (Multi phased collapse)

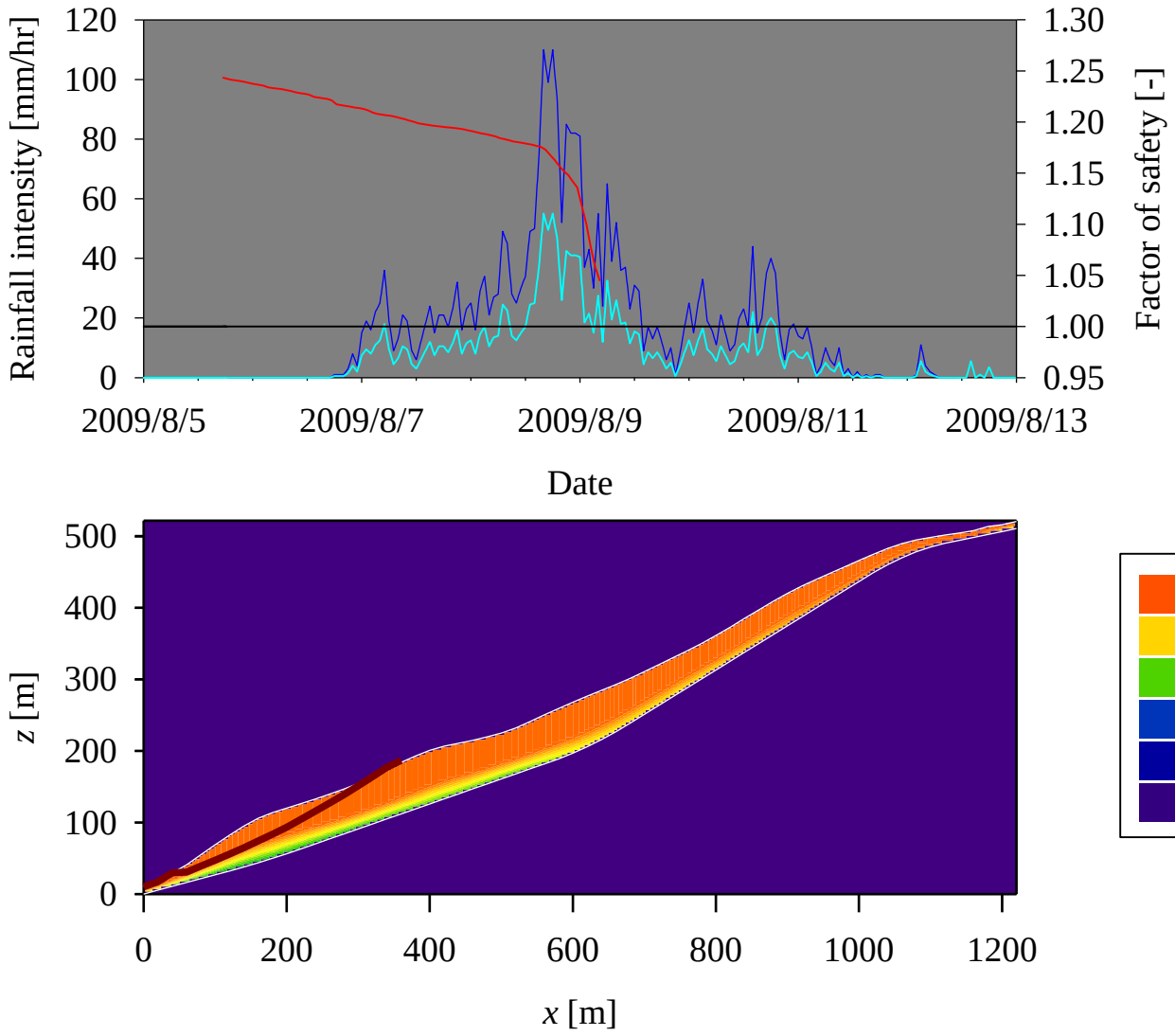
Comparison of shapes of landslide

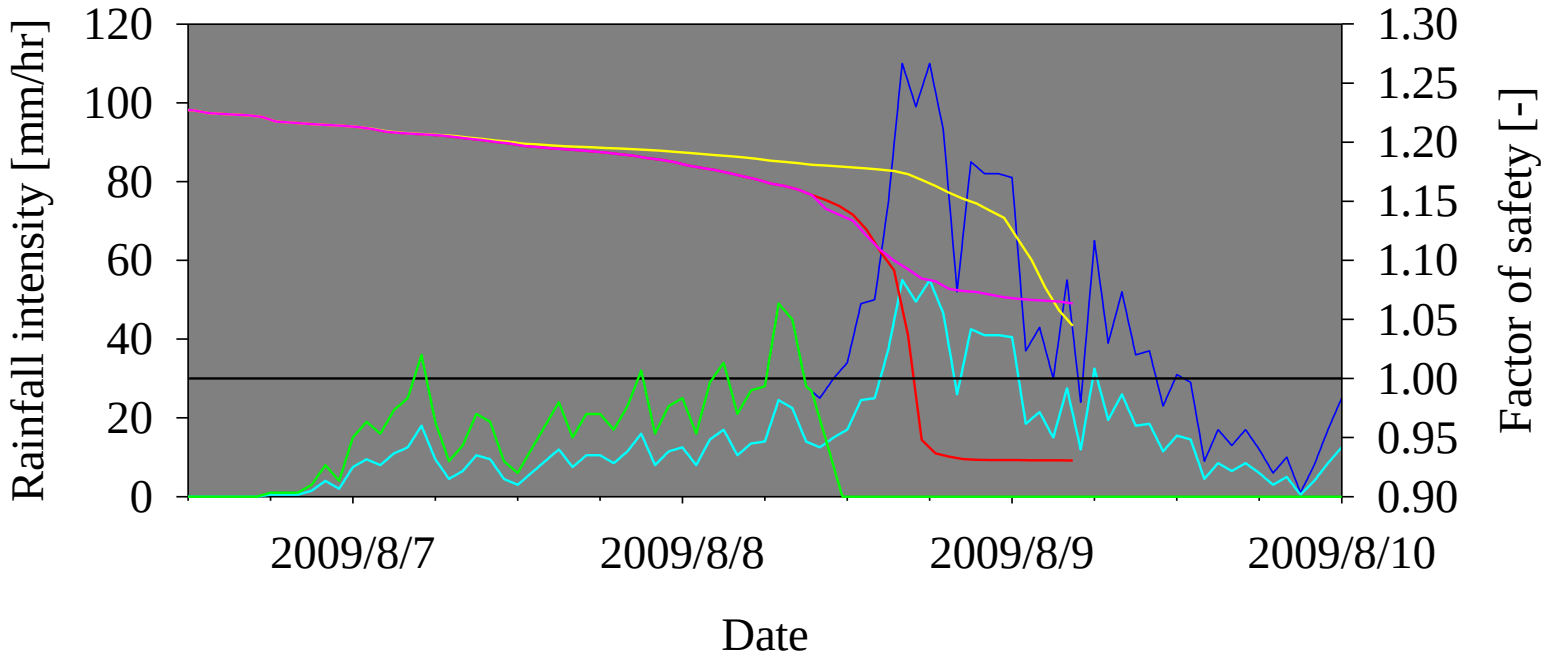


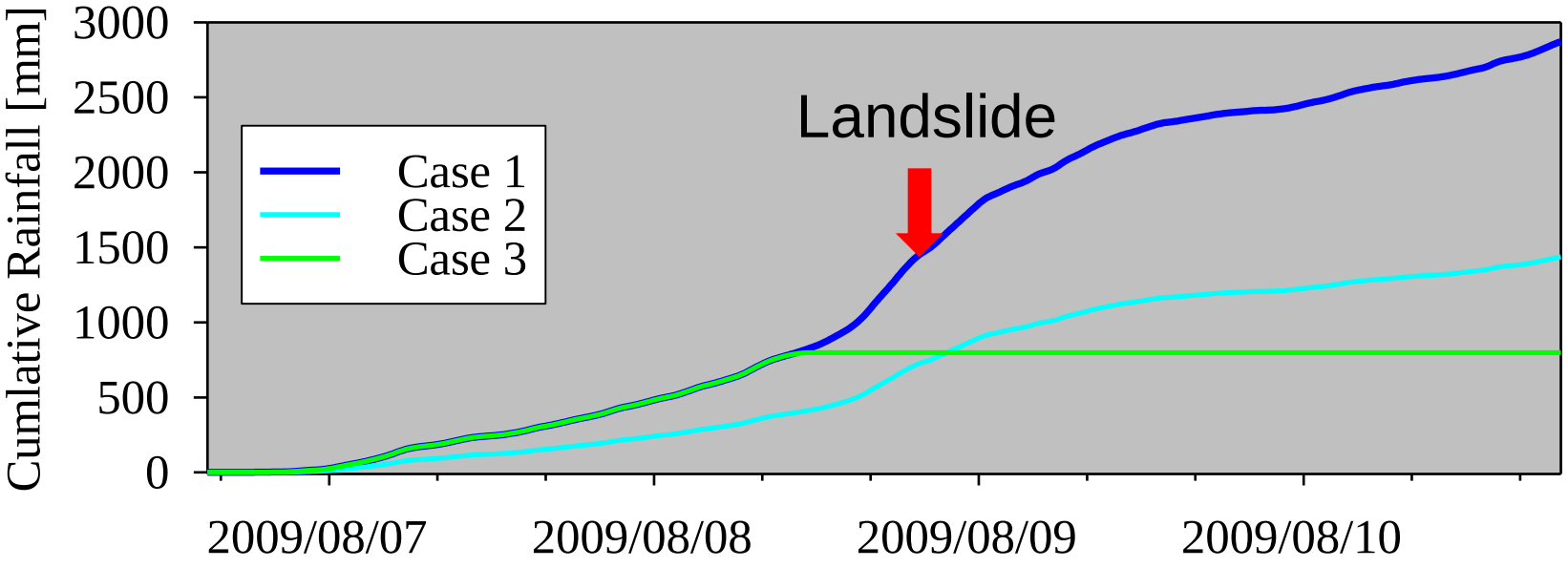
Case 2: Rainfall stops before the peak

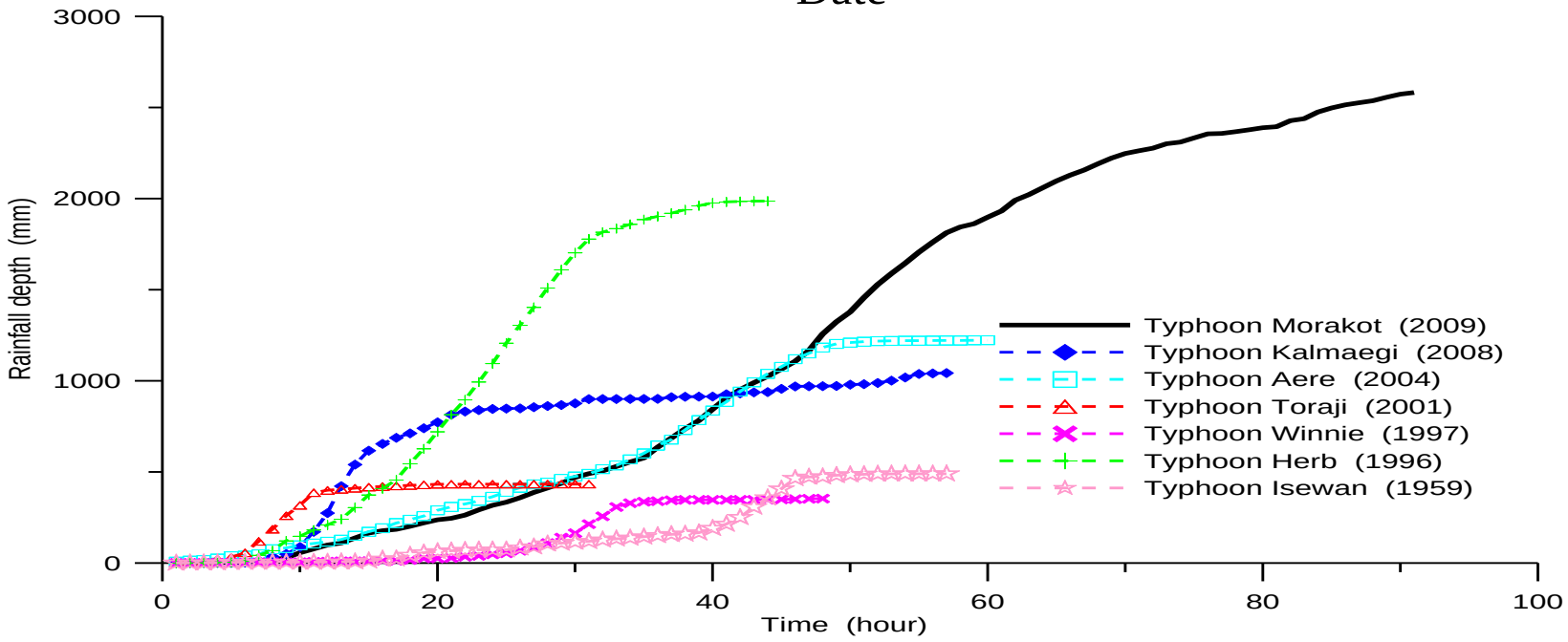


Case 3: 1/2 rainfall intensity




Rainfall intensity [mm/hr]
120
100
80
60
40
20
0
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
Factor of safety [-]
2009/8/7
2009/8/8
2009/8/9
2009/8/10
Date


Cumlative Rainfall [mm]
3000
2500
2000
1500
1000
500
0
Landslide
Case 1
Case 2
Case 3
2009/08/07
2009/08/08
2009/08/09
2009/08/10
Date


Rainfall depth (mm)
3000
2000
1000
0
0
20
40
60
80
100
Time (hour)
Typhoon Morakot (2009)
Typhoon Kalmaegi (2008)
Typhoon Aere (2004)
Typhoon Toraji (2001)
Typhoon Winnie (1997)
Typhoon Herb (1996)
Typhoon Isewan (1959)

Conclusion (so far…)

- The landslide occurred at uppermost 1/3 portion of total slope
- The rainfall infiltrates to 80 m depth of subsurface layer
- The main body of landslide seems to be collapsed in multi phased manner
- Further detailed analysis of the infiltration and slope stability are necessary
- The experience of the landslide in Shaolin village should be utilized for the rainfall threshold analysis in both Taiwan and Japan